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Using remote sensing and traditional ecological knowledge (TEK) to understand mangrove change on the Maroochy River, Queensland, Australia

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ABSTRACT

Mangrove forests support a variety of ecosystem functions and services imperative for ecosystem health. Despite the importance of mangroves, however, mangrove forests worldwide are under threat from human development and climate change. To date, most research on mangrove change in Australia has drawn on approximately 40 years of remotely sensed imagery, a fraction of the time period required to assess spatial change. To improve our understanding of mangrove change, data were collected using historic and current remotely sensed satellite imagery and participatory mapping with Kabi Kabi Traditional Owners to assess mangrove change on the Maroochy River, Queensland, Australia. The results indicate that mangrove extent in the lower Maroochy River has changed significantly since European colonisation in the mid to late 1800s, and declined in recent decades by approximately 30%, a rate similar to global estimates of mangrove loss. Past drivers of change included land clearing for cattle grazing and sugar cane production, and present drivers include agricultural activities, population growth, rapid urbanisation and discharge of pollutants and sewage. These changes have consequences for coastal protection, water purification, biodiversity and cultural services. This research demonstrates how using traditional ecological knowledge (TEK) and remote sensing for understanding ecosystem change, particularly where scientific data are limited, can increase the time period during which change is assessed and enhance the detail and scope of the assessment.

1. Introduction

Mangroves grow exclusively within the intertidal zone of tropical and sub-tropical coastal regions, while saltmarsh ecosystems typically occupy the upper tidal zone but below the highest astronomical tide-mark (Aslan, Rahman, Warren, & Robeson, 2016). These transitional ecotones are uniquely placed where ocean, land and fresh water converge, and perform a number of ecological functions that are vital to the health of near-shore marine environments and surrounding terrestrial systems (Kathiresan & Bingham, 2001). Research on mangroves in the Caribbean Sea (Sedberry & Carter, 1993), Indian Ocean (Pinto & Punchihewa, 1996) and Coral Sea (Morton, 1990) show that ecological functions are highly productive within large mangrove forests (Nagelkerken et al., 2000). The benefits provided by mangroves, however, stretch far beyond ecological boundaries. The estimated financial capital provided by these ecosystems approximates to US$1.6 billion (1997-dollar value) globally each year in ecosystems services (ES), which benefit many coastal communities (Aburto-Oropeza et al., 2008; Costanza et al., 1997). The Millennium Ecosystem Assessment (2005) categorised ES into four key factors: supporting, provisioning, regulating and cultural services. These services include water purification, nutrient cycling, carbon sequestration, biological control, food production, pollution control, shoreline defence, and sense of place and spirituality (Kathiresan & Bingham, 2001; Zedler & Kercher, 2005).

Mangrove and saltmarsh ecotones are sensitive to the onset of both natural and anthropogenic drivers of change (Lovelock et al., 2015). For example, human population growth and changes in desired spatial occupancy has seen more than 50% of the global population relocate to coastal areas prompting rapid development in these regions (Marine, 2006). Consequently, large expanses of coastal ecosystems including wetlands, mangroves and saltmarsh have been removed, reclaimed or heavily degraded, reducing water quality, habitat availability and vital ES (Polidoro et al., 2010). Conditions that are considered to have the greatest impact globally on mangroves include, sea-level rise (SLR), extreme high-water events, storms, and changes in precipitation, temperature and ocean circulation patterns (Gilman, Ellison, Duke, & Field,

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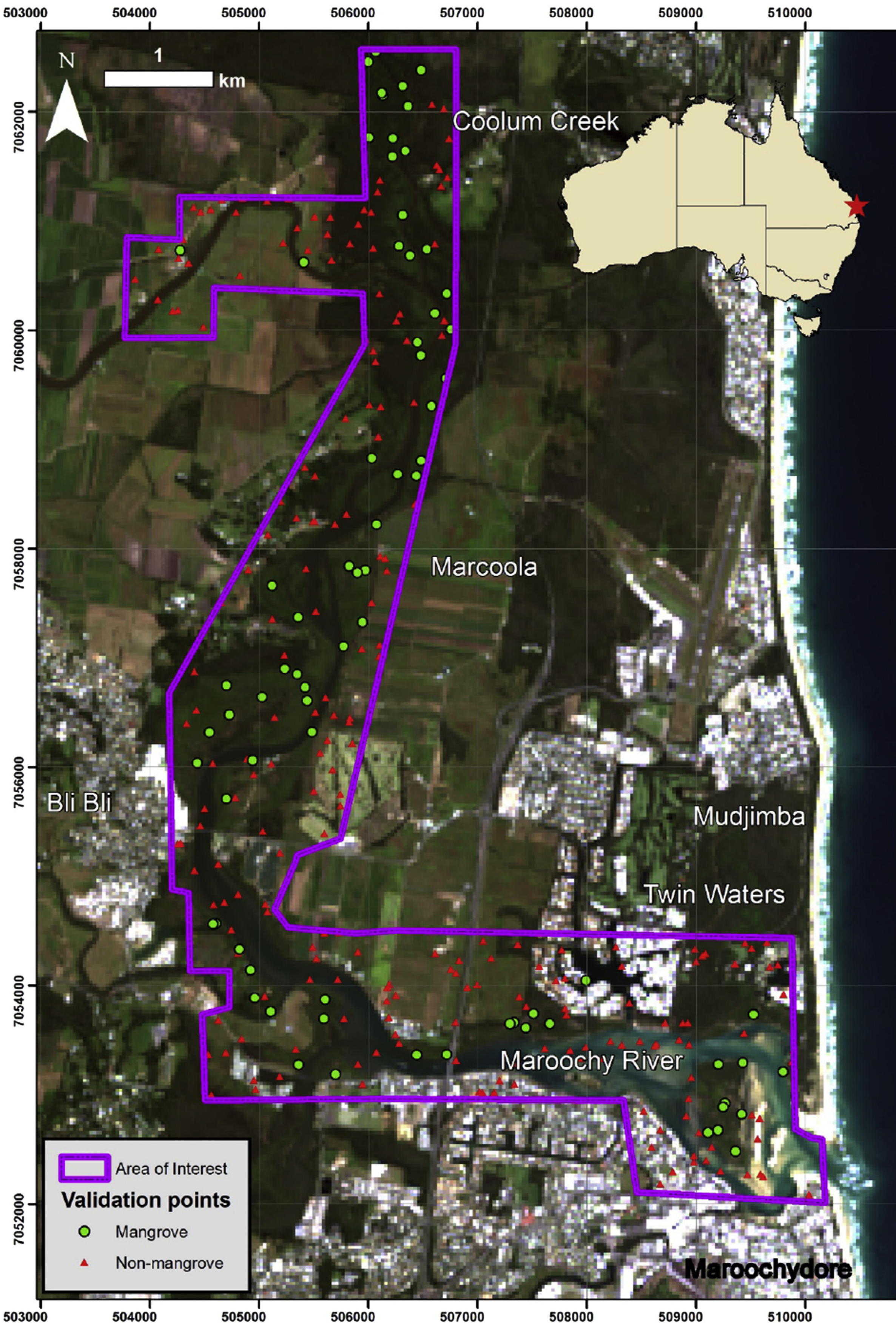

Fig. 1. Location map of the Maroochy River showing the study area defined with Kabi Kabi Traditional Owners (purple polygon) and 500 random sample points used for the calibration and validation of classified images. Source Map: ArcGIS 2016. (GDA94/MGA zone 56 coordinate system). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2008). Rapid SLR is of particular concern as mangroves are unable to keep pace when the rate of sedimentation is exceeded by rising seas (Gilman et al., 2008; Hoegh-Guldberg & Bruno, 2010; Parkinson, Delaune, & White, 1994). Furthermore, with the Earth already committed to some degree of climate change (Cubasch et al., 2013), future climate scenarios anticipate SLR to accelerate, placing additional stress on mangrove and saltmarsh ecosystems (Hoegh-Guldberg & Bruno, 2010; Mengel et al., 2016).

Despite their importance to coastal communities, an estimated 35% of mangrove extent has been lost since the 1980s globally, with current annual losses as high as 2% (Polidoro et al., 2010). Such removal and degradation of mangrove and saltmarsh ecotones has had severe consequences for neighbouring social and ecological systems. For example, by placing additional pressures on fish that utilise mangrove habitats for food, shelter and reproduction, including 80% of all commercially fished species (Lee & Dittmann, 2008). The consequences of such losses are not limited to fish alone and 40% of all animal species restricted to mangrove habitats are now recognised to be at risk of extinction from habitat loss (Greenberg, Maldonado, Droege, & McDonald, 2006).

Assessing mangrove change and implications for ecosystem function and services requires a holistic assessment of the landscape and should include traditional ecological knowledge (TEK) and western scientific knowledge when both are available (Leon et al., 2015). TEK refers to a cumulative body of knowledge, practices and values about the environment obtained through experiences and observations or from rich spiritual teachings of the land and sea which are passed down from one generation to the next (Noongwook, The Native Village ofSavoongaThe Native Village of GambellHuntington, & George, 2007; Pearce, Forde, Willox, & Smit, 2015). TEK is particularly useful for understanding ecosystem change when empirical scientific measurements are limited. In this paper for example, data accrued via satellite imagery was restricted to post-1983, yet it is commonly understood that changes in mangrove extent began prior to this time. To overcome similar challenges, other studies have used TEK and instrumental measurements to assess ecosystem change in a variety of contexts and locations, including, for example, Mapedza, Wright, and Fawcett (2003) in Zimbabwe, Dongus et al. (2007) in Tanzania and Reichel and Frömming (2014) in Switzerland.

The aim of this paper is to assess mangrove change on the Maroochy River, Queensland, Australia using remote sensing and TEK in order to provide a more holistic and longer-term account of the factors and process driving mangrove change. To do so, the objectives are to: (1) document changes in mangrove extent over time; (2) identify key drivers of change in mangrove extent; and (3) examine the links between mangrove change and implications for ecosystem services. The study builds upon previous research with Kabi Kabi Traditional Owners on Indigenous land management and identified mangrove change as a priority concern (Wilson, 2015; Wilson et al., 2018). The following sections provide a brief description of the Maroochy River and Kabi Kabi and the methods employed in the study. The results are then presented and discussed in the context of improving current ecosystem management efforts through the use of remote sensing and TEK to provide a more holistic account of ecosystem change and management options.

2. Study area

2.1. Maroochy River

The research was conducted within the lower catchment of the Maroochy River, located on the Sunshine Coast, Queensland (26°38′29″ S and 153°04′35″ E). Mangrove species including Black Mangrove (*Aegiceras corniculatum*), Grey Mangrove (*Avicennia marina*), Stilted Mangrove (*Rhizophora stylosa*), Milky Mangrove (*Excocaria agallocha*) and Orange Mangrove (*Brugiera gymnorhiza*) are found along the riverbanks (Sunshine Coast Regional Council, 2016). Key research sites along the river were identified in consultation with Kabi Kabi Traditional Owners extending across a total area of ~5795 ha (Fig. 1). Potential sites more than 150 m above sea level were excluded; it is assumed that mangroves do not populate landscapes above this height globally (Aslan et al., 2016). The Maroochy River is largely characterised by subtropical lowlands situated between the Pacific Ocean and Blackall Range and is a vital component of local hydrology, draining 640 km^2 that make up the Maroochy Catchment (Sunshine Coast Regional Council, 2016). Small tributaries carry water runoff from the highlands, depositing it into the larger river system. Tidal records taken near Coolum Creek indicate strong semi-diurnal patterns with tidal ranges between 0.15 and 1.03 m (Maritime Safety Queensland, 2016). Land cover and land use within the lower Maroochy River catchment have undergone significant changes over time, shifting from dynamic, native ecosystems to highly modified agricultural land (Gregory, 1991).

2.2. Human occupancy

Kabi Kabi (also Gubbi Gubbi) peoples are the Traditional Owners and custodians of the Sunshine Coast region described in this paper. The traditional lands of the Kabi Kabi are widespread, spanning some 280 km from Bribie Island to the mouth of the Burrum River and stretching 140 km west from Double Island Point, including Fraser Island, totalling an approximate land area of 22,500 km^2 (Mathew, 1910). Unlike the neighbouring Jinibara nation who officially reclaimed some of their Indigenous land rights through a Native Title determination in 2012, the Kabi Kabi nation are still awaiting determination of their registered Native Title claim.

Prior to colonisation Kabi Kabi Country was a resource rich area with an abundance for flora and fauna, much of which are now locally extinct (e.g. emu, *Dromaius novaehollandiae*) or under threat (e.g. koala, *Phascolarctos cinereus*). Kabi Kabi utilised the Maroochy River system for its cultural and natural resources, including food, shelter, trade and ceremony. They were close observers of nature and held a great depth of TEK (e.g. bio-indicators for food supplies), some of which is still known and practised today. The non-Indigenous population living near the river grew steadily during colonisation beginning around 1890 and continuing through the early half of the 1900s. During this time, the river was used for transportation, delivery of goods and services and recreational activities. Following World War II, the return of service people and a demand for work accelerated work in the cane fields and commercial fishing industries (Gregory, 1991). Consequently, the use of floats, fishing vessels and recreational river boats grew exponentially together with urbanisation. In recent decades, land use within the region has changed once again to sub-urbanised environments to support a rapidly growing population (Fig. 2).

The research was undertaken in partnership with Bunya Bunya Country Aboriginal Corporation, hereafter referred to as BBCAC. BBCAC is a non-profit, family-owned Indigenous land management organization operating on the Sunshine Coast and comprises of 16 members, some who identify as both Kabi Kabi Traditional Owners (Undumbi/Undanbi family group) and Australian South Sea Islanders (Malaita, Solomon Islands), others as historically-connected Aboriginal people (descended from family who were removed from their country), and non-Indigenous relatives. The lands and waters most frequently managed by BBCAC are generally located within, but not limited to, the Maroochy River catchment. BBCAC members have strong physical, emotional and spiritual connections to the Maroochy River (Mooroo-kutchi), which they maintain through their work and family activities such as fishing, shellfish collection and ecological restoration. The Maroochy River holds deep spiritual significance to Kabi Kabi peoples and features in their dreaming stories. Despite the displacement of many ancestors following colonisation, Kabi Kabi continue to have a strong connection to the Maroochy River and a rich knowledge of their 'Country' (Davidson & Ors, n.d.).

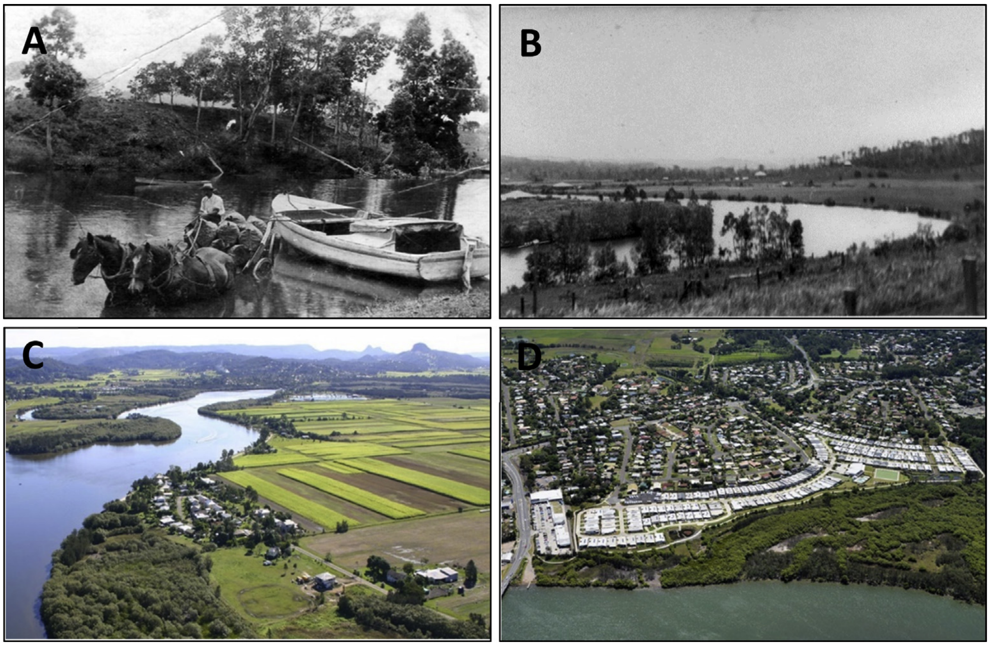

Fig. 2. (A) Oyster farmer at Bli Bli 1891, (B) Maroochy River 1920, (C) Agricultural land 2008, (D) Widespread urbanisation 2016.

3. Methods

Changes in mangrove extent were estimated from spatial data acquired through participatory mapping interviews, satellite imagery and field data. Drivers of change and implications for ecosystem services were then identified from participatory mapping data and secondary data on water quality and river health.

3.1. Participatory mapping interviews

Participatory mapping was held 'on Country' near the Maroochy River in September 2016 with seven members of BBCAC to document TEK of mangrove change (Fig. 3). A purposive sampling strategy was used to recruit participants who were peer-identified as having TEK of the Maroochy River, including mangroves. A description of the research sample is provided in Table 1. The small sample size is due to a limited number of Kabi Kabi TEK holders residing 'on Country' and caring for country in the Maroochy River catchment as a result of forced removal

Table 1
Characteristics of the interview sample with members of BBCAC.

Participant Number	Gender	Indigenous	Years on Country
1	M	Y	> 60
2	M	Y	> 55
3	M	Y	45
4	M	Y	50
5	M	Y	45
6	M	Y	35
7	F	Y	30

Fig. 3. Participatory mapping interviews with members of BBCAC 'on Country' near the Maroochy River.

from the coast until as late as the 1970's. The mail bias (6/1) is likely due to a higher number of male BBCAC members being actively involved in land management on the Maroochy River at the time of the research.

Interviews were open ended and guided by a semi-structured interview guide. The open-ended structure was used to minimise interview bias and to allow participants to share their knowledge and experiences in terms that made sense to them and reflected their priorities. Participants were asked to interact with a scale map (1:11,635) developed using current (25 May 2016), very-high spatial resolution (0.2 m pixel) aerial imagery collected from Nearmap spatial archives (www.nearmap.com). The map was printed on large paper (841 × 1189 mm) and placed on a wood backboard. A clear vinyl sheet (841 × 1189 × 0.75 mm) was placed over the map to create a reusable drawing surface for the participants to write on. Participatory mapping is a standard method of data collection used in ethnography for gathering spatial information and has been widely used by others seeking to integrate TEK with mapping technologies (McCall & Minang, 2005). Interviews were conducted in English and audio recorded. Each interview began by collecting basic demographic information about the participant (i.e. name, age, occupation/means of livelihood, relationship with the river). This was followed by three key questions: (1) how has mangrove extent changed over time? (2) what are the drivers of change? and (3) have changes in mangrove extent effected ecosystem services? Participants were asked to identify areas on the map where mangroves used to be and other areas relevant to mangrove change and river ecosystem health and services. Interviews were complemented with informal meetings and experiential trips on the river with members of BBCAC. These experiences helped contextualise information shared by participants during mapping interviews about mangrove change.

3.2. Data analysis

To prepare the mapping data for digitisation into GIS a set of overlapping photos were taken from approximately 2 m above the map containing data from the 7 participants. Photos were mosaicked, orthorectified and georeferenced (error less than 0.5 pixel) before the information was digitised and extracted as individual GIS vector layers, similar to the methods used by Leon et al. (2015). The high quality of the aerial photograph allowed for precise positioning of current landscape features by community members. The spatial data retrieved included georeferenced information based on GDA94/MGA zone 56 coordinate system, which was integrated into ArcMap GIS software where a measured coordinate grid was applied.

Interview data were transcribed, uploaded to NVivo version 11.4.1 (QSR International), qualitative data analysis software, and analysed using the principles of latent content analysis (Bernard, 2000). The data were scanned to identify common or recurring themes related to mangrove change over time, drivers of change and changes in river ecosystem health and services. Interview data are complemented, when available, with data from secondary sources of information including, population records and predicted future population growth for the Sunshine Coast region, and water quality data (pH, turbidity, dissolved oxygen and salinity) collected by Maroochy Waterwatch between 1996 and 2016 (a community based organization engaged in the protection and enhancement of the Maroochy River catchment and region). Six sampling sites were identified for the assessment of water quality and included EST738, EST344, EST233, COO900, MAR400 and MAR327 (Fig. 4). Sites were selected based on their proximity to the river mouth, surrounding anthropogenic influences, and areas of concern to BBCAC and local Kabi Kabi people as identified during preliminary consultations.

3.3. Remotely sensed and field data

Landsat images spanning 1988–2016 with a clear view of the study area and containing less than 15% cloud cover were selected for change detection analysis (Fig. 5). A total of 23 images from the Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+) and Operational Land Imager (OLI) sensors were downloaded. All images were downloaded from the USGS Global Visualisation Viewer archive (http://glovis.usgs.gov/) and were processed at a Standard Terrain Correction level (LT1) and resampled at 30 m spatial resolution (Table 2). The selection process maintained consistent monthly accounts where possible to reduce uncertainties due to seasonal variability in mangrove leaf phenotypes. Images taken from June through October were the most useful, as these months had the smallest percentage of cloud cover in the region (Bureau of Meteorology, 2016).

Field data were collected in June 2016, with members of BBCAC. During this exercise, the location of mangrove vegetation was plotted at low tide (0.22 m) using a Garmin eTrex 10 handheld GPS with nominal horizontal accuracy of < 10 m (www.garmin.com). Locations of various landscape attributes such as drainage outlets, healthy and unhealthy mangroves, rock walls, and high erosion and sedimentation zones were plotted. This information was used in conjunction with a very high resolution (0.2 m) Nearmap orthophoto mosaic derived from aerial imagery and high-resolution pan-sharpened Quickbird imagery (0.6 m) to calibrate and validate land cover.

A total set of 500 points were assigned to the study area and extracted using a random sampling approach, generated within ArcMap (Fig. 1). Each point was manually classified as “mangrove” or “non-mangrove” based on field data and higher spatial resolution imagery datasets, including Nearmap aerial imagery and QuickBird satellite imagery. These points were then randomly divided into calibration (n = 200) and validation (n = 300) points.

3.4. Data pre-processing and analysis

The workflow undertaken to pre-process and analyse the images is shown in Fig. 4. Radiometric and geometric normalization are critical for change detection analysis. Radiometric corrections were performed using the Carnegie Landsat Analysis System – Lite (CLASlite) software package (Asner, Knapp, Balaji, & Páez-Acosta, 2009) to obtain surface reflectance. CLASlite uses the 6 S radiative transfer model (Vermote, Tanre, Deuze, Herman, & Morcrette, 1997), which simulates the Earth's atmosphere in each satellite image by using data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) sensor.

Terrain corrected (LT1) Landsat images are orthorectified (USGS, 2016). However, some Landsat images do not have ground-control which might introduce uncertainties in change detection analysis due to misregistration (Verbyla & Boles, 2000). To mitigate this, all images were georeferenced to the L8 OLI September 2016 scene (Root Mean Square georeferencing errors < 0.5 pixel).

Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) spectral indices were calculated for further analysis. NDVI is an index derived from the ratio of near-infrared and red spectral information commonly used to map vegetation health (Kerr & Ostrovsky, 2003; Muttitanon & Tripathi, 2005). NDWI is derived from the ratio of near-infrared and middle-infrared radiation often used for interpreting leaf water content, making it particularly useful for the observation of mangrove canopies. Coupling NDVI and NDWI is known to increase overall accuracy of vegetation and land cover assessments (Xu, 2006). The NDVI (Equation (1)) and NDWI (Equation (2)) indices were calculated for images between 1994 and 2015.

$$\mathrm{NDVI} = NIR - Red/NIR + Red \quad (1)$$

$$\mathrm{NDWI} = NIR - SWIR/NIR + SWIR \quad (2)$$

Fig. 4. Location of six Maroochy Waterwatch water quality sampling sites overlayed on 2015 Nearmap Orthophoto mosaic. Source Map: ArcGIS 2016 (GDA94/MGA zone 56 coordinate system).

Remote Sensing Workflow		
	1	Selection of study site (Input from BBCAC)
	2	Selection of images from Landsat archive (1998 – 2016)
	3	Radiometric (CLASlite) and geometric calibration
	4	Spectral indices (NDVI, NDWI)
	5	OBIA training/validation (2016 image)
	6	Classification of images (1998 – 2015)
	7	Post-classification bi-temporal change detection analysis

Fig. 5. Workflow of remote sensing data pre-processing and analysis.

Table 2
Landsat images used for mapping mangrove areas.

Sensor	Month/Year
Landsat 5 Thematic Mapper (TM)	May-88
Landsat 5 Thematic Mapper (TM)	Jun-94
Landsat 5 Thematic Mapper (TM)	Jul-95
Landsat 5 Thematic Mapper (TM)	Jul-96
Landsat 5 Thematic Mapper (TM)	Sep-97
Landsat 5 Thematic Mapper (TM)	May-98
Landsat 7 Enhanced Thematic Mapper Plus (ETM+)	Aug-99
Landsat 7 Enhanced Thematic Mapper Plus (ETM+)	Aug-00
Landsat 7 Enhanced Thematic Mapper Plus (ETM+)	Jul-01
Landsat 7 Enhanced Thematic Mapper Plus (ETM+)	Apr-02
Landsat 7 Enhanced Thematic Mapper Plus (ETM+)	May-03
Landsat 5 Thematic Mapper (TM)	Jul-04
Landsat 5 Thematic Mapper (TM)	Sep-05
Landsat 5 Thematic Mapper (TM)	Jul-06
Landsat 5 Thematic Mapper (TM)	Jun-07
Landsat 5 Thematic Mapper (TM)	Sep-08
Landsat 5 Thematic Mapper (TM)	Sep-09
Landsat 5 Thematic Mapper (TM)	Sep-10
Landsat 5 Thematic Mapper (TM)	Jul-11
Landsat 8 Operational Land Imager (OLI)	Apr-13
Landsat 8 Operational Land Imager (OLI)	Jun-14
Landsat 8 Operational Land Imager (OLI)	Sep-15
Landsat 8 Operational Land Imager (OLI)	Apr-16

The combination of SWIR and near-infrared reflectance reduces data uncertainty swayed by internal leaf structure improving classification results (Gao, 1996). It should be noted that although NDWI provides a clear indication of vegetation water content, it should not be used in isolation as an indicator of vegetation health, but rather as a tool to compliment NDVI (Gao, 1996).

3.5. Classification, accuracy assessment and change detection

An Object-Based Image Analysis (OBIA) approach was used to classify the images. OBIA follows a two-step process were an image is first segmented into groups of similar pixels (objects) and subsequently classified (Blaschke et al., 2014). OBIA have been successfully used to map mangroves extent and change with significant improved accuracy (Heumann, 2011).

OBIA classification was performed using Trimble's eCognition 9.2 software. An initial classification was performed on the most recent Landsat image (April 2016) due to the availability of ground reference data. The image was segmented using the multiresolution segmentation algorithm with a scale-parameter of 15 and compactness and shape factors of 0.1 and 0.5, respectively, which resulted in a total of 15,437 objects. Classification was undertaken using the machine learning Random Forest (RF) classifier. RF uses multiple decision trees to make predictions of class allocation and identifies the best model based on a weighted voting process (Duro, Franklin, & Dubé, 2012). Previous studies have successfully used OBIA approaches and RF classifiers to accurately map vegetation using Landsat imagery (Juel, Groom, Svenning, & Ejrnæs, 2015; Liu, Abd-Elrahman, Morton, & Wilhelm, 2018; Melville, Lucieer, & Aryal, 2018).

Statistics for the 200 calibration points included the mean blue, green, red and near-infrared values, standard deviation of near-infrared and NDVI and NDWI values. Parameters for the RF algorithm included 16 maximum categories, 50 maximum tree number and a 0.01 forest accuracy. The final classification was validated using the 300 validation points and an error matrix was calculated (Congalton & Green, 2008).

The trained RF algorithm was used to classify the remaining images. Post-classification change detection was performed using area statistics between individual classified mangrove areas and a spatially-explicit bi-temporal approach (two-point timescale). The spatially explicit bi-temporal approach provides an efficient direct comparison of the type of change and reduces error propagation from individual image classifications in the final change detection analysis by incorporating detailed *a priori* field-based knowledge and focusing only on a single thematic comparison (Disperati & Virdis, 2015). The expansion/retraction of mangrove cover between 1988 and 2016 was assessed and difference maps were created using ArcGIS software following Albert et al. (2017).

4. Results

4.1. Participatory mapping interviews

Participants described and identified on maps extensive changes in mangrove distribution and extent in the Maroochy River system since European colonisation (approximately 1860). Participants shared how their ancestors would meet among the mangroves to gather food such as fish and crabs, and collect raw materials from the mangrove trees themselves. They identified and described historic meeting and fishing places, some which have now been lost to suburban development, and estimated mangrove distribution and extent prior to European colonisation in 1860 (Fig. 6A). According to the participants, mangrove forests were more widespread within the study area prior to European colonisation, spanning from the mouth of the river in the south to Coolum Creek in the north. In particular, sizable stands of mangroves were noted to have occupied the river banks to the west of Coolum Creek, which suggests that mangrove stands stretched at least 17 km upstream of the river mouth. Participants also identified a fourth island that was once located between Chambers Island, Channel Island and Goat Island to the south-east. The island was historically used by Kabi Kabi for fishing and contained a few small mangrove stands until the island disappeared before 1900. Given the dynamic nature of the lower Maroochy River, it is recognised that natural changes to geomorphic processes may be partially responsible for shifts in the location and size of mangrove populations in some areas.

4.2. Remotely sensed mangrove classification

The classification accuracy based on the 2016 image had values of 82.4%, 50.1% and 74.5% for overall, producer and user accuracies, respectively. Although 85% is typically used as the universal baseline value for maps to be considered accurate, Pontius and Millones (2011) recognised the limitation of universal values, suggesting baseline figures should take individual research questions or study areas into account. As such, the classification accuracy for the 2016 image, assumed to be similar for the remaining dates, was deemed adequate for the

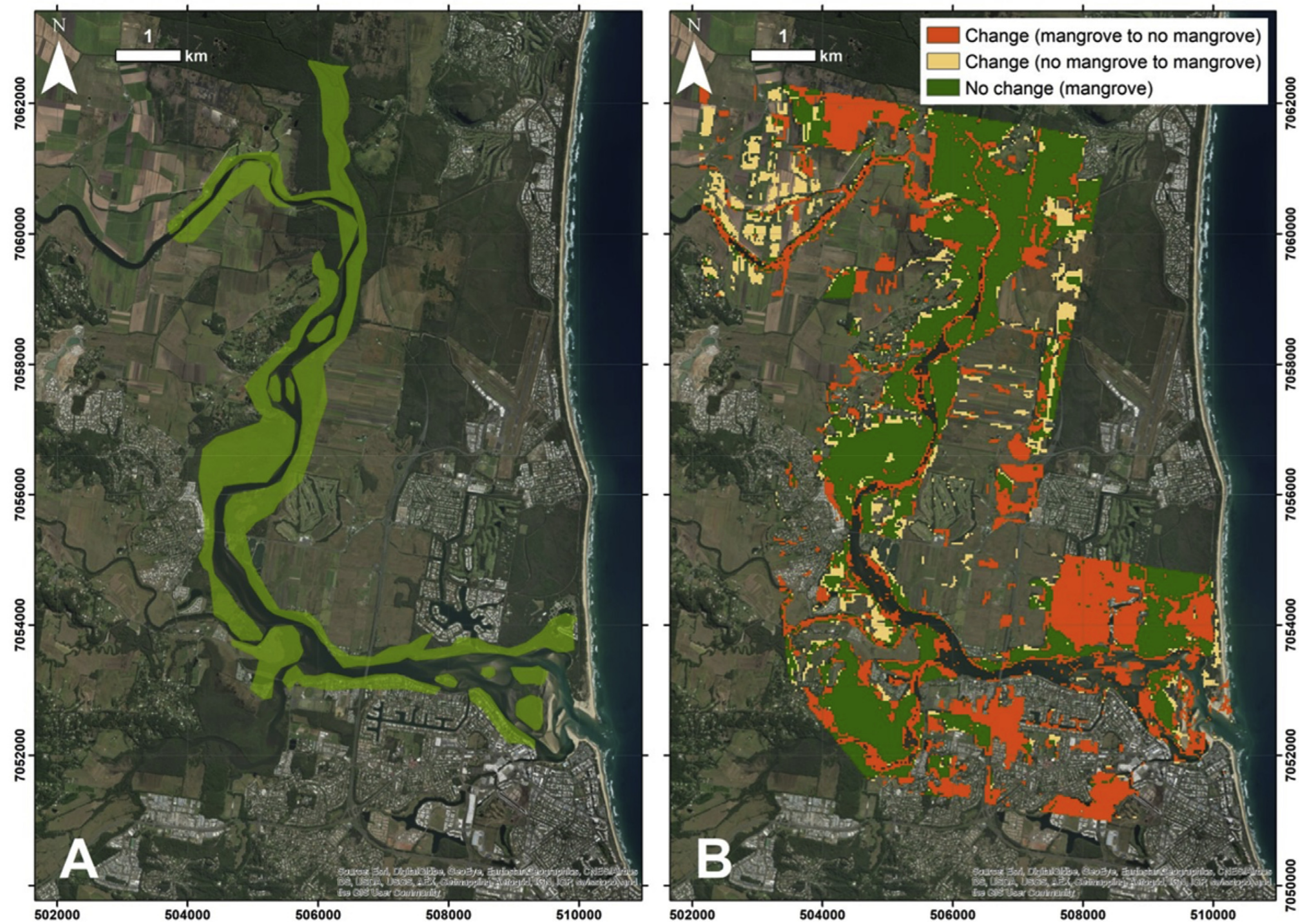

Fig. 6. Approximate representations of (A) mangrove extent pre-colonisation from data collected during participatory mapping interviews with members of BBCAC and (B) changes in mangrove extent between 1988 and 2016 from remotely sensed data. Source Map: ArcGIS 2016. (GDA94/MGA zone 56 coordinate system).

purpose of assessing temporal change in mangrove extent on the Maroochy River. Additionally, by using the post classification bi-temporal analysis, propagation of uncertainties due to single-year classification accuracies were mitigated in the final change detection analysis (Disperati & Virdis, 2015).

From 1988 through 2016, total mangrove area declined by 683 ha across the 5795 ha area of study, a 30% loss or mean annual loss of 24.4 ha/yr^{-1} (Fig. 7). Based on areal statistics derived from individual classification results, in 1994, mangroves covered 1383 ha of the study area and by 1995 declined by 3% to 1342 ha. The spatial change in

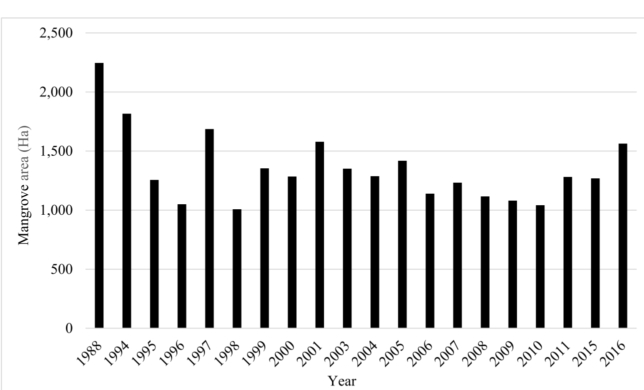

Fig. 7. Estimated mangrove extent across the study area derived from the classification of Landsat imagery (1988–2016).

mangrove coverage is shown for 1988 and 2016 (Fig. 6B). Several regions have undergone change since 1994 however, the largest concentration of habitat loss has occurred at Bli Bli, Marcoola and to the west of Coolum Creek.

4.3. Drivers of change

Drivers of mangrove change in the study area include: farming, pollution, sewage discharge and boating activities (Table 3). These factors are widespread, complex, and have mostly adverse consequences for mangroves.

4.3.1. Farming

European colonisation around the lower Maroochy River during the mid to late 1800s was the primary historic driver of mangrove decline in the area. Kabi Kabi participants described how Elders spoke of the destruction of Country on a scale never witnessed before. Clear-cutting practices were said to have removed large expanses of native vegetation from property boundaries and destroyed several sites culturally significant to the Kabi Kabi nation. This included disturbances to fishing and hunting grounds and the destruction of artefacts along the riverbanks and among mangrove vegetation. Participants explained that this clearing was initially undertaken to support cattle grazing, but a booming sugar industry persuaded many farmers to re-purpose their land from cattle grazing to sugar cane. These activities had a considerable impact on the overall health of the river and the remaining mangrove population. Fertilisers and pesticides were used extensively to increase sugar cane yields, and were washed into the river during

Table 3
Temporal description and identification of key factors driving changes in mangrove extent and associated impacts from PM data.

Estimates Year(s)	Drivers	Impacts	Quotes
Late 1800s – 2016	*Farming*	• Habitat loss • Nutrient runoff • Erosion • Degraded water quality	*"A lot of the land was cleared for cattle grazing before the cane was there [about 130 years ago]" (Participant 1)*
Late 1800s – 2016	*Urbanisation*	• Pollutant and sediment runoff • Removal of cultural sites • Degradation of mangrove and saltmarsh • Urban sprawl • Over fishing • Increased erosion • Invasive weeds	*"At this rate there might be no mangroves left in 50 years" (Participant 3) >* *"More sediment enters the river after rain now … it takes longer for the river to clear up again" (Participant 2)*
1999, 2008, 2012	*Pollution and sewage*	• Fish kills • Noxious weed growth • Degraded water quality • Mangrove dieback • Chemical leaching	*"It let go one night …. , that killed everything" (Participant 1)*
Late 1800's – 2016	*Recreational Boating*	• Structural damage to river bank • Increased pollution/nutrient loads • Over fishing	*"Everybody washes their boats and jet skis on the boat ramp. Even though one or two occurrences won't have much of an affect, an increase in these activities does" (Participant 3)*

heavy rainfall degrading water quality and causing localised mangrove dieback. Severe erosion along the river-bank due to land clearing for farming, particularly along the northern portions of the river, has resulted in bank instability and sedimentation, as observed by Kabi Kabi participants. Mangrove stands that remain along the river banks adjacent to farmlands were considered by all participants to be in very poor condition and unlikely to successfully propagate.

4.3.2. Urbanisation

Current mangrove decline is primarily driven by rapid population growth and urbanisation (Table 3). The population boom following World War II saw rates of infrastructure development, such as housing and roadways, reach levels paralleled only by development by the sugar cane industry. Participants recalled their Elders discussing how their Country was reconstructed into a harsh landscape of foreign values that sought to exploit the land of all its resources. Early stages of development were situated in close proximity to the river mouth and this soon expanded to the south and west reaches of the river. Participants noted that development was for the most part stunted in the northern region of the river system due to transportation difficulties until access to these areas became easier with the construction of the David Low Way bridges at Eudlo Creek, Petrie Creek and Bli Bli, and the Sunshine Motorway bridge in the 1960s. This allowed for easier transportation to otherwise separated quadrants, accelerating urban sprawl across larger areas of the river system.

During the 1960s, infrastructure adjacent to the river was at risk of being undermined by erosion attributed to mangrove loss and natural geomorphic processes. To prevent damage to infrastructure, a revetment was installed to defend against erosive coastal processes, which further removed many mangrove stands along the shoreline. Aside from the direct removal of mangrove habitat, the intensification of urban development, impermeable surfaces and artificial drainage systems were considered by all participants to have drastically altered natural hydrological flow and routed pollutants directly into the river affecting mangrove health and water quality.

The population of the Sunshine Coast has grown from an estimated 5288 persons in 1911 (Commonwealth of Australia, 1911) to 287,539 in 2015 (Sunshine Coast Regional Council, 2015). Maroochydore has experienced some of the largest population growth in recent years compared to other suburbs in the lower Maroochy River catchment area. Estimates in 2015 show that Maroochydore supports a population of approximately 16,090 compared to 11,209 in Bli Bli, 10,690 in Marcoola, and 6524 in Yandina (Sunshine Coast Regional Council, 2015). The combination of these suburbs alone accounts for approximately 44,513 people or 15.5% of the total population of the Sunshine Coast. Such population growth so close to the Maroochy River puts increased pressure on the ecosystem directly, through recreational use, and indirectly through pollution and run-off.

4.3.3. Pollution and sewage discharge

Local sewage treatment plants were noted to be adversely affecting mangrove and river health (Table 3). Participants identified four sewage treatment plants: Maroochydore, Nambour, Coolum and Suncoast facilities that discharge treated waste (secondary treatment) water directly into the waterway. Intense rainfall events and higher than average tides were believed to place additional stress on treatment plants, causing system overflows that release raw, untreated sewage directly into the river. Participants noted that these overflows were a regular occurrence, particularly in recent years where substantial leaks occurred in 2008 and 2012. Some participants recalled a major leak in the 1990s, which caused large fish kills and negatively affected the quality of the river water. With the projected onset of more intense rainfall and rising sea level due to a warming climate, participants believe that the sewage treatment plants and contamination from sewage leaks will continue to degrade mangrove and river health into the future.

4.3.4. Boating activities

Intensified use of the river for recreational purposes was identified as a key stressor affecting mangroves (Table 3). An increasing number of boats and jet skis using the river have already caused severe erosion of riverbanks, particularly along areas where mangrove vegetation is already sparse. In addition to the adverse impact on mangroves, erosion also produces turbid water with higher nutrient loads. Participants also noted that many boats come up the river to fish and that they have witnessed over-fishing on several occasions where users were seen taking more catch than is permitted for the fishery, or taking females instead of males as required for some species. Finally, participants also stressed their concern for the health of the river from people washing their boats and jet skis with cleaning agents adjacent to the river.

4.4. Implications for ecosystem services

Decline in mangrove extent around the lower Maroochy River since European colonisation has affected the ability of mangrove forests to perform vital ecosystem functions and services. These include, for example, coastal protection, water purification, biodiversity and habitat, and cultural services.

4.4.1. Coastal protection

The removal of mangrove vegetation prior to 1900 has caused long-term implications for erosion and coastal defence. Participants explained that the complex physiology and root structure of mangroves is responsible for sediment retention and structural integrity of the riverbank and also for protecting vital riparian habitat situated behind mangrove vegetation. In contrast, land cover change to cattle grazing lands and sugar cane fields replaced deep-rooted mangrove systems with shallow-rooted vegetation. Consequently, shallow-rooted vegetation has a limited capacity to reinforce the surrounding soil, making the soil more easily eroded by weather, mass failure, rainfall and tidal fluctuations. A serious concern related to mangrove decline is the capacity of the river system to cope with enhanced threats from climate change, particularly rising sea level and more frequent and intense extreme weather events. Participants describe the river as a dynamic system that is at the mercy of extreme weather and ocean conditions, and mangroves offer refuge against volatile conditions, reducing inland flooding and slowing flood-water velocity. Remaining large mangrove stands in the river protect vital riparian habitats used by Kabi Kabi and others for food and recreation.

4.4.2. Water purification

Reduced mangrove abundance has limited the filtering and nutrient cycling services performed by mangroves. Participants unanimously agreed that water quality in the Maroochy River has been deteriorating since colonisation. Kabi Kabi Elders explained that mangroves are filters of the waterway, responsible for cleansing the river of sediment and toxins. They described the waterway as once strong, fertile and pure, and in the past, turbid conditions after heavy rainfall were said to have subsided and water quality returned to normal within a few days. After large-scale land clearing prior to 1900 and the onset of urbanisation in the 1950s, participants said that the duration of turbid conditions following rainfall has dramatically increased, taking up to two weeks to return to regular conditions following comparatively smaller rainfall events. Participants shared that today the “normal” clarity of the river is a shadow of what their Elders say the river used to be.

4.4.3. Biodiversity

Species diversity and abundance of flora and fauna in the lower Maroochy River has changed dramatically post-colonisation. In terms of mangroves and riparian vegetation, species diversity is believed to be consistent with the past, but species abundance has changed. Land clearing practices have decreased the spatial extent of many mangrove species, including Black Mangrove (*Aegiceras corniculatum*), Stilted Mangrove (*Rhizophora stylosa*) and Grey Mangrove (*Avicennia marina*) and replaced riparian land with sugar cane plantations. Moreover, enhanced sediment loads within the waterway, from shoreline erosion also negatively affect the diversity and abundance of aquatic biota. Several locations formerly considered by Kabi Kabi to be prime fishing areas are now considered to be poor. This is believed to be the result of overfishing by non-Indigenous fishers, urbanisation, and the loss of more than 90% of sea grass meadows (Waycott et al., 2009). Additionally, participants have observed increasingly fewer mud crabs along much of the river and most crabs being caught are female.

4.4.4. Cultural services

Changes in the river system have considerable consequences for cultural services and sites. The disruption and conversion of mangrove habitat and adjacent land for cattle grazing and sugar cane has destroyed numerous sites that are culturally significant to Kabi Kabi. Shell middens, scar trees (canoe trees), and grinding stones were largely decimated, erasing thousands of years of aboriginal cultural heritage. Moreover, the establishment of private property boundaries and development of infrastructure has limited access of local Kabi Kabi to traditional hunting and fishing sites. One Elder Participant shared that he can no longer access several of his favourite fishing sites because private developments have been built along the river, blocking access. Accelerated erosion from reduced bank stabilisation by mangroves continues to threaten aboriginal cultural sites and reduce water quality of the river system.

4.5. Remote sensing and secondary data

Spatial analysis of mangrove vegetation highlights changes to mangrove forest distribution and size over time; however, available secondary data shows little change to river health over time. It is known that the marginalisation of mangrove habitat along the southern extent of the river directly impacts the productivity of the system to perform various functions and services which may impact the abundance of reliant aquatic species and affect species diversity (Duke et al., 2007). We also know that reduced coverage of mangrove vegetation has implications for the structural integrity of the river bank, erosion prevention and coastal defence, while further increasing sediment loading in the waterway and contributing to degraded water quality (Duke et al., 2007). That said, however, water quality data (pH, turbidity, dissolved oxygen and salinity) collected by Maroochy Waterwatch at the six sites identified in Fig. 4 between 1996 and 2016 shows that there have been minimal changes in water quality over time, with the exception of infrequent elevations in turbidity, likely associated with heavy rain events (Fig. 8).

5. Discussion

Prior to European colonisation of the region in the 1800s, mangrove extent was widespread along much of the lower Maroochy River, beginning at the mouth of the river and continuing beyond Coolum Creek. Only a fraction of the virgin mangrove forest remains today. The decline in mangroves during the last century is not surprising given the large-scale land conversions to pastoral grazing, sugar cane production, and more recent suburban development. Today, mangrove forests in Queensland are protected under the Fisheries Act 1994, but despite legislative protection, mean mangrove extent in the Maroochy River has declined by 30% from 1988 to 2016, similar to global mangrove estimates since the 1980s (Polidoro et al., 2010). This decline may be partially attributed to the ecological relationship between mangroves and agricultural runoff. Grey mangrove (*Avicennia marina*) is the dominant species found along the Maroochy River and is particularly sensitive to chemicals associated with agricultural run-off (Duke, Bell, Pederson, Roelfsema, & Bengtson Nash, 2005). This finding suggests that legislative protection of mangroves may be futile if agricultural practices are not improved to further reduce agricultural run-off.

Monitoring spatial changes in mangrove extent with Landsat imagery is very beneficial but restricted in terms of spatial resolution and availability prior the 1970s. Satellite imagery showed general changes in mangrove extent over a short period of time (~40 years), leaving questions as to what the mangrove extent was prior to European colonisation. Given the limitations of satellite imagery, it was beneficial to draw on other sources of spatial information to extend the period of time when changes in mangrove extent could be assessed. Local Kabi Kabi Traditional Owners continue to live in close association with the Maroochy River ecosystem and hold a cumulative body of knowledge about ecosystem components and processes. This includes past knowledge of mangroves and salt marshes, passed down between generations through oral transmission, and contemporary understanding of

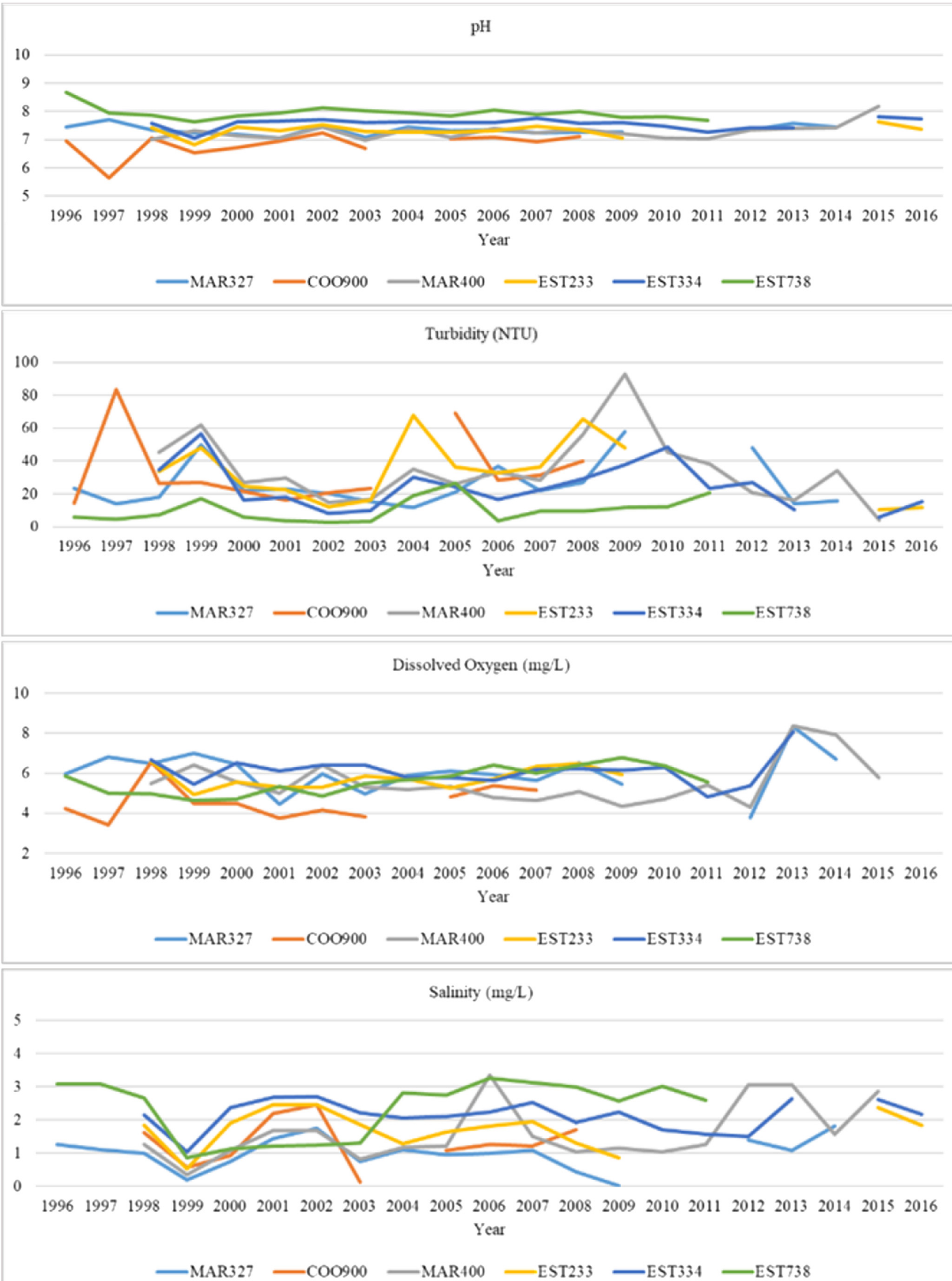

Fig. 8. Physico-chemical measurements (pH, turbidity, dissolved oxygen, salinity) collected from water samples at six sites on the Maroochy River between 1996 and 2016 (see Fig. 4 for location of sampling sites). Source: Maroochy Waterwatch 2016.

ecosystem processes and change. Taken together, this knowledge, referred to here as TEK, provided a longer-term perspective on changes in mangrove extent that pre-dated European colonisation. Traditional Owners were also able to describe key drivers of change and detailed observations of changes in ecosystem function and services.

Traditional Owners identified several interconnected factors driving changes in mangrove extent, including: farming, urbanisation, pollution, sewage discharge and recreational boating. The largest historic change in mangrove extent was the result of mangrove removal and land clearing practices employed by early settlers for cattle grazing and sugar cane production. Mangrove forests were disturbed along most of the study area with the exception of parcels of land near the river mouth. Today, rapid urbanisation along the river is evident and likely to continue or even accelerate. Housing developments are being built on areas where mangroves historically grew eliminating possibilities of ecosystem recovery, and salt marshes are being destroyed with negative effects on mangroves. Runoff from agriculture, suburban developments, and sewage treatment plants is entering the waterway and has adversely affected mangrove health, including widespread dieback. This is typically the result of gross nitrogen, potassium and phosphorous absorption, which promotes above ground biomass production including new shoots and foliage but in some cases, stunts the production of below ground biomass such as complex root systems (Lovelock, Ball, Martin, & Feller, 2009). In this case, mangroves become more sensitive to saline conditions and periods of low rainfall and are highly compromised by erosional processes (Lovelock et al., 2009).

The finding that water quality data collected at the selected sites on the river showed minimal changes in water quality over the past twenty years, but participants described significant changes in water quality and river health highlights the difference between the two knowledge systems. The water sampling measurements taken by Maroochy Waterwatch focused on single attributes in the environment (pH, turbidity, dissolved oxygen and salinity) and were taken at certain locations on the river and at specific times. Such data is thus limited spatially and temporally. In contrast, TEK is a holistic body of knowledge that is cumulated over time and incorporates new observations and experiences with past knowledge, to build a comprehensive understanding of the environment. Traditional Owners were able to describe, in detail, changes in river health over time that are not readily captured by standard water quality sampling techniques. Overall, participants describe that changes in water quality have been negative and the current health of the river is compromised from its pre-colonial state. It is noteworthy that the baseline health of the river used by local government is based on post-European colonisation assessments, whereas, Traditional Owners describe a river ecosystem pre-European colonisation that was much healthier.

TEK and scientific research agree that mangrove forest size and structure are key attributes of a healthy ecosystem (Duke et al., 2007). The current state of mangrove decline provides a bleak outlook for the health of the Maroochy River. Steady declines in forest size and a breakdown in structure suggest that mangrove habitats are increasingly at risk of reaching an ecological tipping point (Sidle, Benson, Carriger, & Kamai, 2013). This refers to a state at which the environment can no longer maintain natural functions or processes, causing ecosystems to drastically shift or collapse (Sidle et al., 2013). Such declines are cause for concern for fisheries and associated expenditure within the lower Maroochy River (estimated at $AUD 19 million yr $^{-1}$), as most recreational and commercially desirable species there depend on mangrove habitat or associated food chains (Department of Agriculture and Fisheries, 2016).

6. Conclusion

The findings of this research have important implications for ecosystem management generally, and the management of the Maroochy River specifically. First, where local or traditional ecological knowledge of an ecosystem exists, it should be included in studies of ecosystem health and change. TEK generally covers a longer time period than most instrumental measurements, is holistic, highly detailed, and is continually being updated in light of new observations. Second, legislation to protect mangroves needs to be extended to protect areas of historic mangrove cover to allow restoration and recovery. Third, current ecosystem management efforts may be more effective if ecosystem health benchmarks closely reflect that of an uncompromised ecosystem. The integration of TEK in this study offers new insights into the distribution and extent of mangroves not captured by instrumental measurements, which can be used to compare and guide natural resource management and conservation efforts. Using remote sensing and TEK, when available, to examine ecosystem change provides a more holistic and detailed understanding of change and allows us to transcend common spatial and temporal barriers faced by many remote sensing projects.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2018.03.006.

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